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Volume 13 AUGUST, 1943 Number 2

Journal of Sedimentary Petrology

A Publication of the Society of Economic Paleontologists and Mineralogists
a Division of
The American Association of Petroleum Geologists

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Journal of Sedimentary Petrology

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The subscription price of the *Journal of Sedimentary Petrology* is $3.00 per year prepaid to addresses in the United States.

Single numbers, $1.50 each.

Postage is charged extra for all other countries: 40 cents on annual subscriptions (total $3.40).

The *Journal* will furnish reprints at cost. Orders should accompany corrected galley proof.

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GEORGE BANTA PUBLISHING COMPANY, MENASHA, WISCONSIN, U.S.A.

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JOURNAL OF SEDIMENTARY PETROLOGY, VOL. 13, NO. 2, PP. 47–57
FIGS. 1–7, TABLES 1–3, AUGUST, 1943

USE OF THE MICROPROJECTOR IN THE MECHANICAL ANALYSIS OF SMALL SAMPLES OF RIVER SAND

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ABSTRACT

A method is described by which the size-distribution of very small samples may be determined by microprojection. Test analyses of four sands indicate that the data so obtained are comparable with data obtained by sieve analysis. The method has been used extensively for textural analysis of suspended-load samples, and can be used whenever sufficient material is not available for sieving.

INTRODUCTION

In detailed studies of suspended sediment transportation, the mechanical analyses of very small samples of river sand frequently are required.[1] Often only a few milligrams of sediment are available for analysis. Such samples are not suitable for analysis by the use of sieves or the customary sedimentation methods. Because of its convenience, sieving has been widely used in sedimentary analysis where ample quantities of material ordinarily are available. It is advantageous, therefore, to employ methods on small samples which yield results comparable to those obtained by sieving. A satisfactory technique, which utilizes a microprojector for analyzing these minute samples, has been developed at the Sedimentation Division laboratory of the Soil Conservation Service. The size-weight frequency distributions determined by the counting technique described in this paper agree very well with those determined by sieving with appropriately calibrated sieves.

DESCRIPTION OF TECHNIQUE

The use of the microscope for measurements of particle size is by no means new. In recent years, many workers have successfully applied this method in the study of particulate industrial products such as pigments, fillers, precipitates, and cement. In such substances, the particle size encountered is usually less than the lower limit of sieving, the particles also having essentially the same specific gravity and shape. Statistical diameters are sought which can be used to compute such properties of the material as specific surface. In natural sands, the particles vary in both specific gravity and shape. Here the emphasis is placed on the size distribution of the sediment rather than on a single statistical diameter, and the size distribution of such relatively large particles is easily obtained by sieving. These differences probably account for the fact that microscopic measurement has not been used to any great extent for the mechanical analysis of sedimentary samples of sand size.

The method to be described involves the projection of the magnified images of the particles upon a ground glass plate, classification of the particles on the basis of the measurement of a single intermediate diameter, counting of the grains in each class, and the conversion of number frequency to weight frequency by the use of conversion factors, which are nothing more than the cube of the arithmetic mean of the class limits.

A special type of microscope slide (fig. 1) is used for mounting the sediment sample. This consists of an ordinary glass slide, one by three inches, to which has been cemented a cardboard strip in the center of which a round hole, three quar-

[1] Anderson, A. G. The distribution of suspended sediment in a natural stream. Published in the 1942 Transactions of the American Geophysical Union, pt. 2, pp. 678–683.

ters of an inch in diameter, has been punched. A shallow counting cell is thus formed. The sediment is transferred to this cell and covered with a seven-eighths inch square cover glass. A strip of

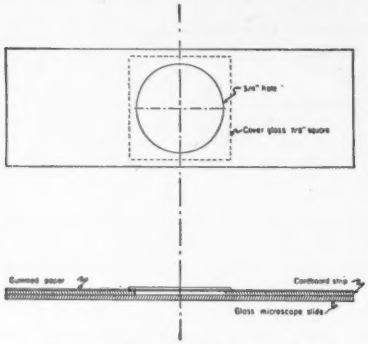

FIG. 1.—Microscope slide used for mounting samples.

gummed paper, also one by three inches, and having a hole corresponding to that in the cardboard strip, is then moistened and pressed into position over the cover glass, thereby holding it in place but permitting full view of the counting cell. Sample numbers and other notations may be written upon the paper strip. Cell depths of 0.75 and 1.3 millimeters have been used, choice of depth being governed by the maximum particle size to be mounted. Slides of this type have been prepared according to the author's specifications by the W. H. Curtin Company of Houston, Texas.

A Promar microscopic projection apparatus equipped with a fixed mechanical stage is used for projecting the images of grains upon an eight by ten inch ground glass plate. The microprojector is set up beneath a suitable table (fig. 2a) in the top of which a hole is cut to accommodate the glass plate. Since all measurements are made on the upper surface of the glass plate, a double advantage is secured; that of a horizontal working surface and that of non-interference from the worker's shadow. Focusing of the microscope is done from the table top by means of a simple extension device. The procedure for analysis is as follows:

The sedimentary particles are first distributed uniformly over the bottom of the cell by tapping the slide lightly with a pencil. Uniformity of distribution is important and may be checked by a rapid inspection of the slide under low magnification. When a satisfactory distribution has been attained, the slide is carefully placed in position on the mechanical stage and the images of the grains are projected on the glass plate. The plate is ruled as shown in figure 2b. When measuring grains, only the central portion of the field delineated by the square ABCD is used.

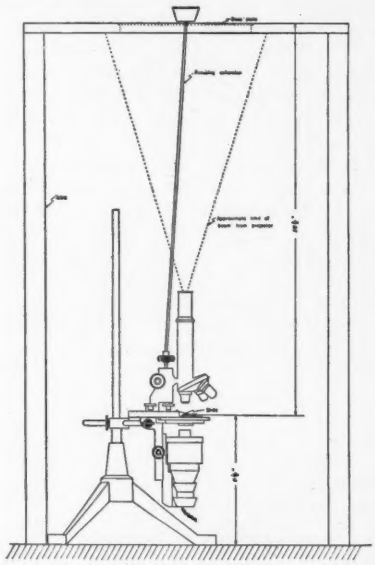

FIG. 2a.—Diagrammatic sketch of apparatus.

Three magnifications are employed. The position of the projector with respect to the table remains fixed, the different magnifications being secured by interchange of two objectives and one ocular.

Magnifications and other pertinent data are given in table 1.

Grains coarser than 0.246 millimeter are measured first, using a magnification of 29 diameters. For these grains the entire slide is covered, starting at the left and proceeding across the slide by cover-

related to the sizing obtained by sieves. Assuming that the particles will tend to lie in their most stable position with their smallest diameters normal to the plane of the projection if free to move when the slide is gently tapped, the intermediate diameter is considered to be that diame-

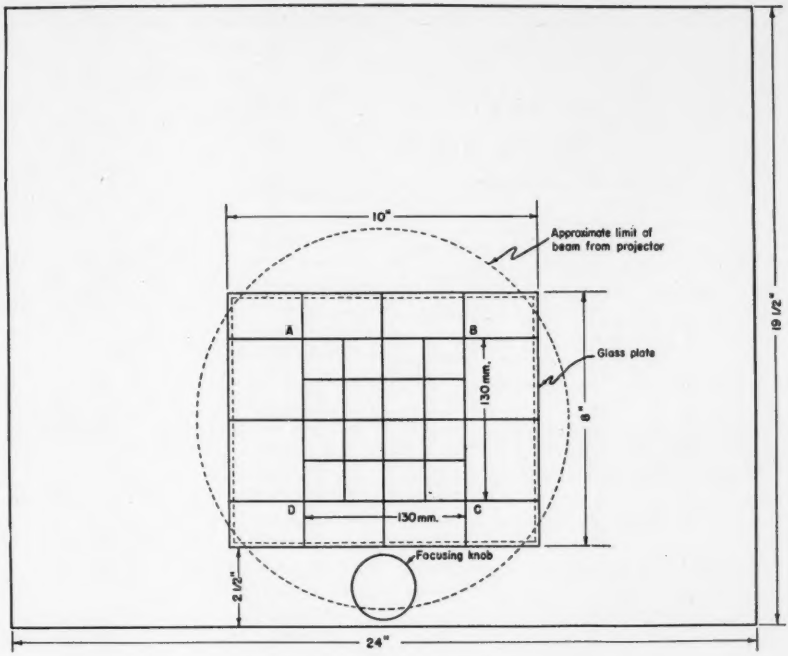

FIG. 2b.—Top of projector table.

ing successive strips of width determined by the two lines on the ground glass plate, AD and BC. The smaller coordinate rulings facilitate the counting. Actual diameters of the grains are not recorded. Instead, a series of classes whose limits correspond to the nominal openings of standard sieves are used. Grains falling within each class are tallied on a suitable record sheet (fig. 3).

Particles are classified on the basis of the intermediate diameter most closely

ter of the projected image which would control the passage of the particle through a circular opening (fig. 4).

To classify the grains, use is made of the flat, flexible, triangular, celluloid scale illustrated in figure 5. On this scale the limits of the size classes covered by each magnification are drawn. Fine graduation lines are cut on the celluloid surface with a razor blade and India ink drawn into the incisions by capillary action. This results in a very fine but

TABLE 1. *Magnifications used for microprojection measurements.*

Magnification	Objective	Ocular	Size range covered
			mm.
29×	11×	—	0.246–
62×	26×	—	0.074–0.246
180×	26×	5×	0.01 –0.074

easily visible graduation. The scale for each magnification is prepared by use of a stage micrometer ruled in 0.01 millimeter intervals.

After all grains larger than 0.246 millimeter have been tallied for the entire slide, grains falling within the limits of 0.074 millimeter to 0.246 millimeter are classified. All grains of these sizes on the slide are not counted. Instead, the slide is sampled by counting only the grains in a strip taken along the diameter of the counting cell, the width of the strip being defined by the distance between the lines AD and BC on the glass plate. The number of grains in each size class in this strip is multiplied by a suitable factor to obtain an estimate of the total number of grains for the entire slide. This "area factor" is the ratio of the area of the circular counting cell, in which the grains are contained, to the area of the strip, or "traverse" covered. To obtain the total area of the counting cell, two measurements of the diameter are made at right angles to each other under a magnification of 62 diameters, using the lines on the glass plate and a millimeter scale. These two measurements are averaged, the average is corrected for magnification, and the total area computed from the true average diameter thus obtained. The area of the "traverse," or strip covered, is computed from measurements of the length and width of the strip made at the same magnification and converted to the true measurements.

The final step is the measurement of grains less than 0.074 millimeter in size. A magnification of 180 diameters is used. A traverse similar to that for the preceding sizes is made along one diameter of the slide and the "area factor" computed in the same manner.

CALCULATIONS

The record sheet for a typical microcount on coarse suspended sediment from a water sample taken in the Enoree River is shown in figure 3. The original sample was separated into coarse and fine portions by wet sieving on a 250-mesh screen (nominal opening, 0.061 mm.). From the mechanical analysis of the coarse portion, concentrations of the various sizes in parts per million have been computed. The steps in the calculation of the data are as follows:

1. Compute the average diameter of the counting cell. Average the two measurements given and divide by the magnification.
2. Compute the area of the counting cell from the average diameter obtained in 1.
3. Record the total number of tallies for each size class in column 1.
4. In column 2 (D^3), the cube of the arithmetic mean of the limits of each size class is given. If in any size class greater than 0.246 millimeter, less than five grains has been tallied, the actual measured intermediate diameters should be shown. If such is the case, average the diameters given, cube the result, and replace the D^3 given for that class by the new D^3 obtained. The same procedure is adopted for the open class at the top.
5. Compute the areas of the traverses covered and the "area factors" which are obtained by dividing the area of the counting cell by the area of each traverse. For those size

classes in which all grains in the entire counting cell were tallied, the area factor is equal to unity. Insert the area factors in column 3.

6. In column 4, insert the product of columns 1, 2, and 3.
7. Add the figures of column 4 and record the sum.
8. Divide the figure for each size class in column 4 by the total of column 4, multiply by 100, and insert in column 5.
9. Multiply each figure in column 5 by the total concentration of sediment >0.061 millimeter (in p.p.m.) and divide by 100. Record the result in column 6 as the concentration (p.p.m.) of each grade size in the original water sample.

EXPERIMENTAL VERIFICATION OF ASSUMPTIONS

In his researches on the theory of grinding, Martin has shown that for crushed sand, $V/d^3 = \text{constant } B$ where V is the statistical volume, d is the statistical diameter of the particles, and B is the volume constant of the powder. The volume constant, B, was found to be the same for various homogenous grades of crushed sand. If a uniform specific gravity is assumed for the particles, a similar weight constant must also exist.

In the calculations for the technique described in this paper, the fundamental assumption is made, that if natural sands are graded on the basis of intermediate diameters, the average weight of the

U.S. DEPARTMENT OF AGRICULTURE
SOIL CONSERVATION SERVICE
SEDIMENTATION DIVISION LABORATORY

MECHANICAL ANALYSIS BY MICROPROJECTION

Sample No. E-2-18-60-SW-13-35-1 Bottle No. 430
Location: Enoree River, S.C. At gaging station upstream from Sedimentation Laboratory, 12 feet from left water edge.
Taken by: A.G.A.
Water depth: 3.00 ft. Dist. from bed: 0.15 ft.
Sample tube No. 1 Time submerged: 48.0 sec.

Wt. of sample and bottle: 646.0 g.
Wt. of bottle: 372.5 g.
Wt. of sample: 273.5 g.
Wt. of sediment > 0.061 mm: 0.0173 g. Concentration: 63 PPM
Wt. of sediment < 0.061 mm: 0.1857 g. Concentration: 678 PPM
Remarks:

M	Class Limits Intermediate diameter, mm.		Class No.	Tally 10	20	30	40	50	60	70	80	90	100	Total number grains counted	Area covered	D^3	Area factor	No. Σ D^3 × Area factor	Weight frac. %	Conc. PPM
29 x	0.991-		9											0	Entire cell		-	-	-	-
29 x	0.701-	0.991	8	// Measured diameters = 0.962, 0.866 mm.										2	" "	5781 / 6686	1.00	1.528	8.3	52
29 x	0.495-	0.701	7	//// ///										12	" "	0.214	1.00	2.568	14.0	88
29 x	0.351-	0.495	6	//// //// //// //// //// //// ////										35	" "	0.0757	1.00	2.650	14.4	91
29 x	0.246-	0.351	5	//// //// //// //// //// //// ////

grains in any size class is proportional to the cube of the arithmetic mean of the class limits, or

$$W_A = KD^3$$

where W_A = average weight of a grain in any size class

D = arithmetic mean of class limits

K = constant which includes the shape and specific gravity factors and is the same for all classes whether composed of large or small particles.

The validity of this assumption was tested experimentally by segregating a sufficient number of grains of each class on the basis of actual microscopic measurement of intermediate diameters to permit weighing. The average particle weight for each size class was then calculated. Due to the tedious nature of the task involved in isolating the grains, the 61-micron to 74-micron class was omitted. The results as shown in table 2 indicate that the assumption is valid for Enoree River sand.

As previously stated, particles were classified on the basis of intermediate diameters in order to obtain data comparable to that derived from sieving. If the sieve openings were circular, sieves would grade the particles strictly on this basis, assuming that the grains had sufficient opportunity to orient themselves correctly. Since the openings are square (or approximately so) the influence of the shape of the grains becomes important. For this reason, if a sieve separate is ex-

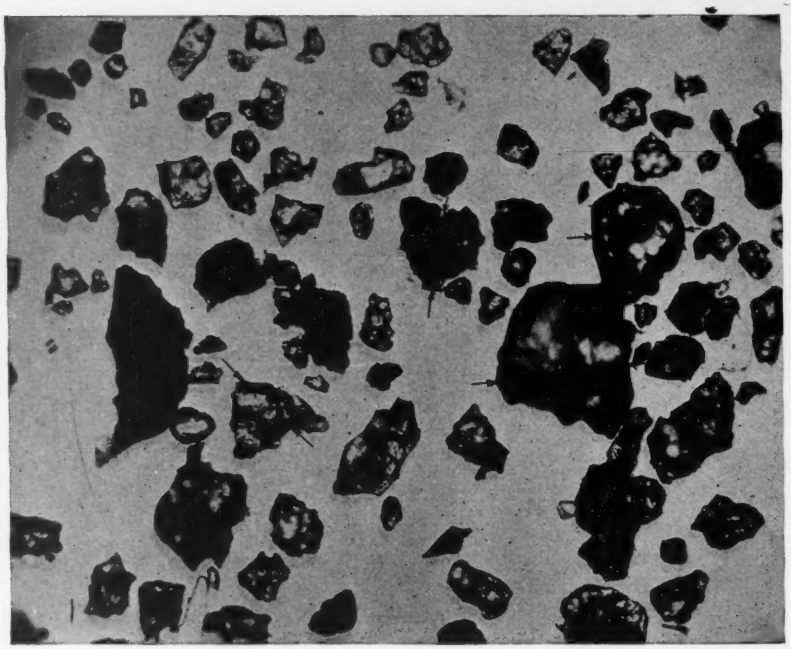

FIG. 4a.—Microphotograph of coarse suspended sediment obtained from a water sample of the Enoree River. Material <0.061 mm. removed by wet sieving. Points of measurement of intermediate diameter of typical grains indicated by arrows. ×22.

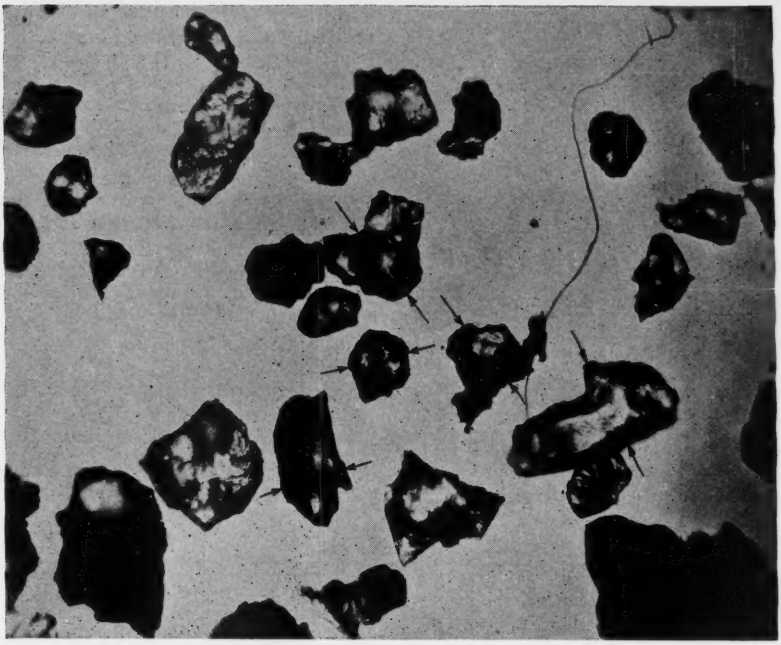

FIG. 4b.—Microphotograph of coarse suspended sediment obtained from a water sample of the Enoree River. Material <0.061 mm. removed by wet sieving. Points of measurement of intermediate diameter of typical grains indicated by arrows. ×47.

amined under the microscope, it will be found to contain many particles whose intermediate diameters do not fall within the limits defined by the nominal openings of the sieves used. Size-weight distributions obtained by sieving, if plotted on the basis of nominal sieve openings, are not comparable, therefore, to the

TABLE 2. *Experimental determination of shape and specific gravity constant for various size grades in a representative sample.*

Class	No. of grains	Total weight	Average weight	D^3	K
Mm.		Mg.	Mg.		
0.701–0.991	307	221.12	0.721	0.606	0.119
.495– .701	439	102.62	.234	.214	.109
.351– .495	645	51.57	.0800	.0757	.106
.246– .351	1,407	41.90	.0298	.0267	.112
.175– .246	2,384	26.60	.0112	.00939	.119
.124– .175	2,295	9.70	.00423	.00338	.125
.074– .124	2,794	3.80	.00136	.00097	.140
				Mean=	.119

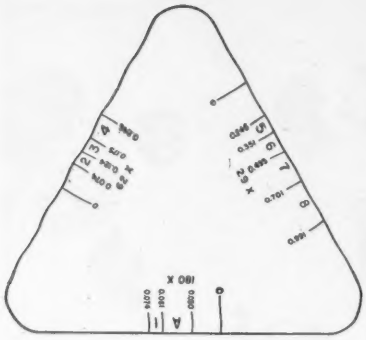

FIG. 5.—Scale used for microcounts of particles of sand size.

distributions obtained by actual measurement of intermediate diameter.

Hatch has suggested a method of calibrating sieves on the basis of the median size by weight of the separate retained on each sieve. Microscopic examination of sieve separates reveals that the size-number frequency distributions follow the logarithmic-probability law. Therefore, the median weight size becomes the geometric mean size by weight. Hatch derived the following transformation equation for calculating the geometric mean weight size from the parameters of the size number-frequency curve obtained by direct microscopic measurement:

$$\log Mg' = \log Mg + 6.9078 \log^2 \delta_g$$

where

Mg' = geometric mean size by weight
Mg = geometric mean size by number
δ_g = standard geometric deviation

A graphic method of deriving the necessary parameters of the number fre-

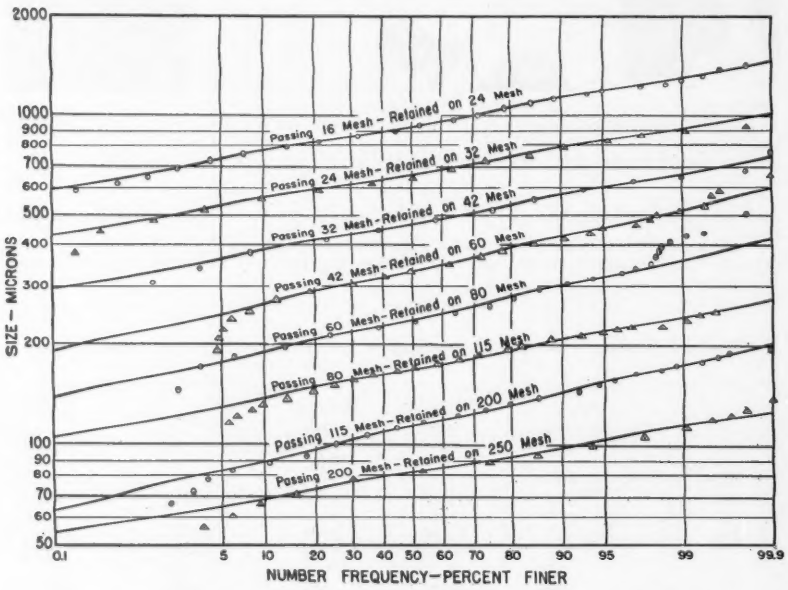

FIG. 6.—Size-number frequency distributions for sieve separates of Enoree River sand. Sieving time 15 minutes.

quency curve is given by Hatch and Choate. The size-number frequency distribution of each sieve separate is plotted on logarithmic probability paper yielding a straight line. The geometric mean is that value obtained by reading the fifty per cent size.

$$\delta_g = \frac{84.13 \text{ per cent size}}{50 \text{ per cent size}} = \frac{50 \text{ per cent size}}{15.87 \text{ per cent size}}.$$

The geometric mean size by weight for each sieve separate is then computed from these parameters. This geometric mean weight size, which is also the median weight size, is taken as the calibration size of the sieve. Then, in using the calibrated sieves in an analysis, the per cent by weight less than a particular calibration size is equal to the per cent by weight of material passing this sieve plus one-half of the per cent by weight retained on that sieve.

Size-weight frequency distributions obtained by the use of sieves calibrated as above should be comparable to those obtained by the counting technique described in this paper, if intermediate diameters are the basis of the sieve calibrations. To test this experimentally, a set of standard sieves ranging in nominal openings from 701 microns to 61 microns was calibrated by the above method using intermediate diameters for classifying the particles. A representative sample of Enoree River sand was sieved and the size-number frequency distribution of the separates determined by measurement. In order to avoid an open class for the top sieve, a 991 micron sieve was used above the 701 micron sieve during the separation. A standard sieving technique involving a shaking time of 15 minutes on a Ro-Tap machine was used. The size-number frequency distributions for the separates retained on each sieve are plotted in figure 6. Straight lines have been fitted by eye to the plotted points. Table 3 gives the parameters derived from these curves, including the median weight size or calibration size for each sieve.

TABLE 3. *Calibration data for sieve separates.*

Sieve limits				Mg	84.13 per cent size	δg	Mg′
Passing		Retained on					
Mesh	Nominal opening	Mesh	Nominal opening				
	Microns		*Microns*	*Microns*	*Microns*		*Microns*
16	991	24	701	925	1007	1.089	945
24	701	32	495	660	759	1.150	700
32	495	42	351	469	545	1.162	501
42	351	60	246	338	403	1.192	371
60	246	80	175	240	288	1.200	265
80	175	115	124	169	199	1.178	183
115	124	200	74	113	137	1.212	126
200	74	250	61	82	94	1.146	87

Four samples of Enoree River sand passing the 991 micron sieve and having different modes were analyzed using the standard sieving technique. A very small sample was then split from each by means of an Otto microsplit. This small sample was analyzed by the microprojection method. In figure 7 the size-weight distribution curves obtained by counting are compared with those derived by plotting sieve weight against nominal opening and calibration size. The agreement between the counting method and sieving plotted on the basis of the calibrates sizes is striking.

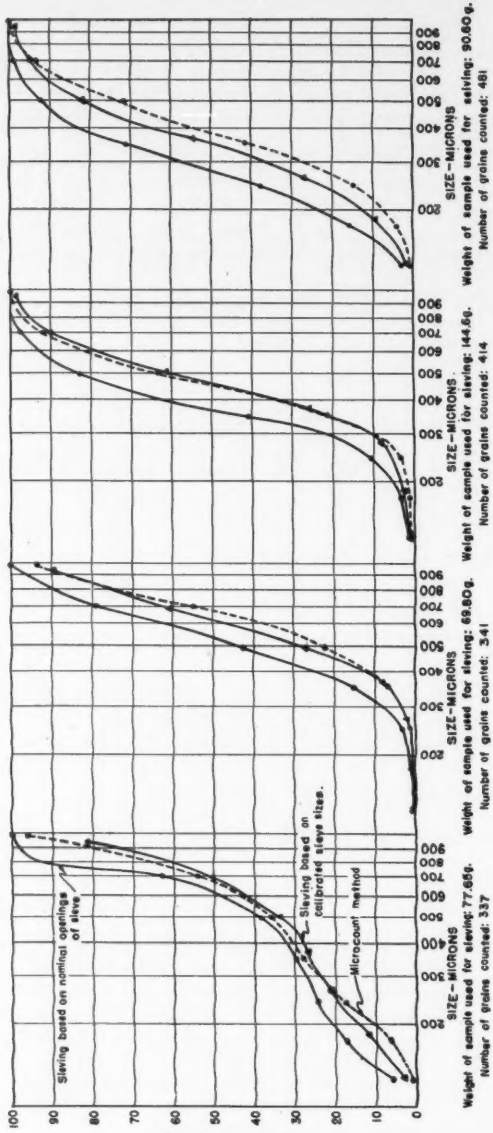
Percent finer (by weight)
Sieving based on nominal openings of sieve
Sieving based on calibrated sieve sizes.
Microcount method
SIZE—MICRONS
Weight of sample used for sieving: 77.65g.
Number of grains counted: 337
Weight of sample used for sieving: 69.80g.
Number of grains counted: 341
Weight of sample used for sieving: 144.6g.
Number of grains counted: 414
Weight of sample used for sieving: 90.60g.
Number of grains counted: 481

FIG. 7.—Size-weight frequency curves derived from counting data compared with curves derived from sieving.

CONCLUSIONS

For Enoree River sands, or similar material, number frequencies may be converted to weight frequencies by multiplying by the cube of the arithmetic mean of the class limits. The weight frequencies thus obtained are comparable to those obtained by sieving on screens calibrated on the basis of the median weight size of the retained material.

Frequency counts may be conveniently made by means of a microprojector, a projection table, and a special microscope slide. The time required for a typical analysis is approximately one hour.

ACKNOWLEDGMENTS

The writer is indebted to Mr. A. G. Anderson, Dr. H. A. Einstein, Dr. Gordon Rittenhouse, and Dr. E. M. Thorpe, for many valuable suggestions and criticisms. The careful work of Harold D. Stalvey, who assisted with many of the microscopic measurements, is worthy of note.

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JOURNAL OF SEDIMENTARY PETROLOGY, VOL. 13, NO. 2, PP. 58–68,
FIGS. 1–6, AUGUST, 1943

GRAPHIC REPRESENTATION OF CHEMICAL WEATHERING

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ABSTRACT

The several graphic devices available for use with studies of chemical weathering are analytically reviewed. The specific advantages and disadvantages of each are noted. A modification of existing methods, combining a number of their more desirable aspects, is proposed and illustrated.

INTRODUCTION

Rock-weathering constitutes the initial stage in sediment generation. The progress and nature of purely physical alterations are expressible in terms of size, soundness and spatial distribution of the resulting fragments. Chemical weathering is a more complicated as well as a much more important affair involving many processes and variables. Studies of this aspect of weathering comprise chemical and mineralogical analyses of suites of samples, each of which should include representatives of fresh rock, of intermediate stages and of the weathered product. Unfortunately, such comprehensive investigations are very few. This necessitates full exploitation of the available data and the complexity of those data makes some form of graphic treatment desirable if not mandatory.

Several graphic methods of representing rock decomposition are in current use, but there seems to be little general appreciation, on the part of students, of the principles underlying these schemes and of their individual merits and demerits. This paper is addressed, therefore, to students of sedimentation. It briefly reviews the relevant graphic methods and considers the factors which should guide one's choice in specific instances. While the discussion is directed towards the handling of sets of chemical analyses, it also applies, in part and with modifications, to mineralogical data.

ACKNOWLEDGMENTS

The writer is grateful for criticisms by Prof. A. O. Woodford of Pomona College, and by his colleagues, Dr. V. C. Kelley and Dr. C. L. Gibson of the University of New Mexico.

GENERAL CONSIDERATIONS

The upshot of chemical weathering is the differential removal of constituents except water; weathered rock is essentially a residual product. In some situations, translocation of materials within the zone of weathering determines the character of the products. This may or may not involve the formation of stable secondary substances. Even in such instances, however, the strongly differential effects on the several constituents should be shown by the graphic treatment used.

Analyses are usually reported in weight-percentage of the oxides of the elements. This form is useful if one is concerned with tonnages as in mining work. It is also satisfactory if the data are used for direct comparison of the quantities of each component in unaltered and altered rock; that is, in the form of ratios involving only individual substances. In all other cases, however, weathering studies are clarified if weight-percentages are changed into molecular ratios. This is accomplished by dividing each of them in turn by the sum of the atomic weights which they represent.

The advantages of using molecular ratios in this sort of problem are summarized by Jenny (1941) as follows:

> . . . we are not so much interested in the weight changes of the soil constituents as in changes in their atomic and molecular proportions. Stoichiometric relationships are more clearly brought out by molecular data than by weight figures. In the second place, chemistry has shown that chemical laws assume the simplest form when expressed in molecular relationships.

It is often convenient or necessary to compare groups of individual substances. In such cases, the use of molecular ratios is mandatory since otherwise the heavier constituents would be, in effect, unduly weighted, often obscuring the variations of lighter substances which are quite as important to the comparison.

Basically, the graphic presentations compare one or more properties of specimens of variably altered rock. Their value may be judged by a number of standards including: rationality, intelligibility, implicit assumptions, general applicability, ease of preparation, and the emphasis placed on one or another aspect of weathering. No single method is universally or solely applicable. Some require very complete data: others serve well where the data are incomplete, and, finally, one is not always interested, even in a single locality, in bringing out the same relationships.

The comparison of analyses in weathering studies is accomplished in three distinct ways, each of which includes two or more variants. These major groups of graphic method may be briefly characterized as follows:

I. Some component is assumed to remain constant in quantity during rock alteration. For each of the remaining components, in turn, the amount which would be present in the weathered rock, had it retained its initial relation to the "constant" constituent, is then calculated.

II. The quantities, or percentages, of the individual substances in the altered and unaltered rock are directly compared.

III. Comparison is made of the ratios between certain groups of substances in the altered rock and in the fresh rock.

THE AVAILABLE METHODS

I

Methods of working up data based on assuming some substance or group of substances fixed during alteration have been widely used, although the results have seldom been shown in graphic form. Merrill (1906) made use of two quantities. First, the rock-percentage lost due to removal of each constituent which may be expressed: $A_f - A_w \cdot C_f / C_w$ where the subscripts refer to the fresh (f) and weathered (w) rock, and A and C are respectively weight-percentages of the variable and the (assumed) non-variant constituents. An example is given in figure 1 which makes use of data given by Goldich (1938) and assumes alumina

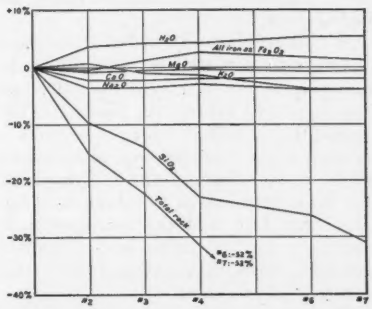

FIG. 1.—Loss in terms of weight-percentage of unaltered rock, assuming Al_2O_3 constant. Goldich's data (Morton gneiss). His analysis #5 omitted as definitely aberrent.

constant. The analysis of sample #5 is omitted from consideration as being definitely aberrant, presumably, due to source-rock variation.

The second quantity used by Merrill may be expressed by the same symbols as before as $(A_w \cdot C_f)/(A_f \cdot C_w)$. This is the

per cent of each constituent, referent to its initial (fresh rock) quantity, retained in the weathered product. The difference between this quantity and 100 representing the percentage lost, is also used. An example is given in figure 2, which

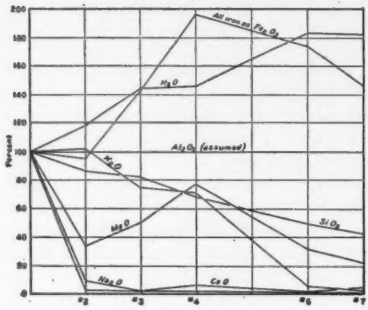

FIG. 2.—Weight-percentage of each constituent retained, relative to its initial quantity. Same data as in figure 1.

utilizes the same data as figure 1. In these calculations all FeO is recast as Fe_2O_3.

In interpreting Merrill's quantities, an implicit assumption is ordinarily made that the alteration, except for H_2O, has been a purely subtractive process. This assumption is possibly quite as hazardous as that of constancy of some component. In the case of figures 1 and 2, either iron has been introduced, or alumina must have been lost, and the assumption of constancy for the latter is ill-founded. Possibly, both have suffered loss, the iron to a lesser extent.

The figures bring out two other points of interest. It appears that adequate representation of the weathering of any rock requires analyses of the products at a number of stages in the process. Second, the relative orders and rates of removal of the constituents are especially well shown even though the assumption of constancy of some component is ill-founded. The use of mol-percentages instead of weight-percentages in these computations would scarcely be justified under ordinary circumstances. The rates of removal of the several constituents might, in the first case, be somewhat more clearly brought out, but the quantities derived could have no stoichiometric significance. In the computations leading to figure 2, use of mol-percentage could have no significance whatever.

The value of the methods of group I is subject to two limitations: first, the insecurity of the assumptions involved, and, second, the omission from consideration of relative amounts or combining proportions. This latter weakness involves an inability to indicate actual compounds present during weathering and the nature of the end products being approached.

II

In direct graphic comparisons of the quantities of individual components in altered and fresh rock, each analysis may be plotted along one of a series of parallel straight lines, or the ratios between the percentages of each substance in weathered and unweathered material may be plotted as such. In the first case, the possible spacings of the parallel lines introduce the variant methods treated under A and B below. The latter case in considered under C.

A

The simplest way in which to compare the quantities of the individual constituents in two analyses is to plot them on

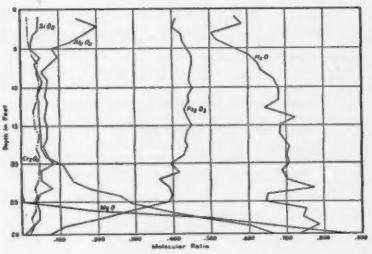

FIG. 3.—Recomputed from analyses of iron ore, eastern Cuba, given by Leith and Mead.

parallel lines to some convenient scale as shown in figure 3. Such "rectilinear" graphs have been widely used. Either weight-percentages or molecular ratios may be used, according as one's interest is economic or chemical. Commonly, as in the illustration given, the spacing of the lines corresponds to the vertical separation of the material analyzed in the field. The method may be varied by using logarithmic scales, in which case the ratios, between the amounts of any constituent in the two samples, may be visually estimated from the separation of the corresponding two points of the adjacent scales.

The advantages of this sort of graph include the following: (1) no assumptions are made as to constancy of any constituent or as to groupings and relations in their behavior; (2) the actual relative proportions in each sample are not obscured; (3) there are essentially no computations; (4) the graph is simple to plot and read; (5) it can be sucessfully used with very incomplete sets of data.

B

The products of rock weathering, like many magmatic differentiates, are related to an initial stage by progressive subtraction of material. This being the case, it is not strange that the 'variation diagram,' which has been so successful in igneous investigations, has been utilized in weathering studies. In the variation diagram, as in the rectilinear graph, each analysis is plotted on a single vertical straight line. The spacing of the lines corresponds to the variations of some designated constituent.

In igneous studies, the substance against whose variation all the others are plotted, usually silica, is one which is present in nearly all possible subtractive compounds except iron oxides etc. In such a case, if the rocks analyzed are derived by progressive subtraction of material from a single melt, all the points corresponding to any oxide lie on a relatively smooth curve. In weathering there is, unfortunately, no single substance which is removed in all stages of the alteration, as is silica in differentiating magmas. Instead, the elements are removed for the most part singly, in combination with anions. Hence, the same sort of base for a variation diagram is not available. However, the percentage

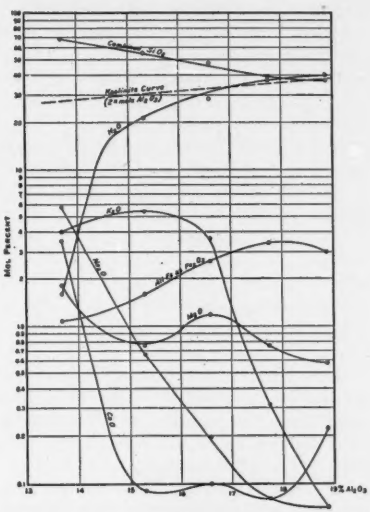

FIG. 4.—Mol-percentage variation diagram, plotted against alumina. Weathering of granite-gneiss, according to Goldich's data.

of any relatively immobile constituent must vary antipathetically with the removal of all others. Thus free silica or titania would be available in some rocks. Goldich (1938) makes use of alumina. It is necessary that the substance chosen should vary consistently and not have a maximum or minimum within the series.

Figure 4 is an adaptation of the common variation diagram, in which mol-percentage instead of weight-percentage is used, so as to bring out the combining proportions. The other constituents are plotted against alumina, and, in addition, a curve, proper to the composition of kaolinite, is drawn. It is significant of

the trend that the silica and H_2O curves of Goldich's suite meet the kaolinite curve at the right. In order to plot values varying from 0.1 to nearly 7.0 on the same graph without undue loss of accuracy in the lower part of the range, a logarithmic vertical scale is used. This device avoids the use of different scales for plotting the several constituents, which is a common but complicating solution. Considerable violence has been exercised in smoothing the lime and magnesia curves in the figure, the values for these two being erratic, due presumably, to slight source-rock variations.

It is evident that the variation diagram shares the advantages of the rectilinear graph previously discussed. Where the spatial relations of the stages of alterations are of importance, as in the technologies, including agriculture, the variation diagram is less satisfactory. Where the chronologic relations (i.e., rates of change) are of concern, the two methods should be equally effective whenever the vertical spacing of the samples has been accurately determined in the field, and is used in setting up the rectilinear graph. This follows from the probability that both vertical field-spacing and the variations in quantity of some chosen constituent are functions of duration of weathering. That these functions are not determinate, in general, and are undoubtedly complex, does not alter this view. It is in those cases in which the vertical field-spacing cannot be determined that the variation diagram will continue to be of special value.

Several circumstances can arise to limit the usefulness of the variation diagram. Juxtaposition of different source materials or the intervention of processes other than the comminutive and solvent ones characteristic of weathering may be mentioned. The latter case would obtain where coagulations of weathering products resulted in secondary stable substances, e.g., allophanoids.

C

The quantities of the individual constituents may also be compared by plotting the ratios of the weight-percentages or of the mol-percentages of each constituent in the unaltered rock to its corresponding value in the altered rock. The first, third and fifth, of the specific advantages credited to rectilinear and variation diagrams (II A), are retained in this method; the second is lost. The fourth is also lost, since the resultant graph has a significance which is not readily grasped without considerable practice. Further, if more than one or two comparisons are made on the same figure, the resultant confusion of lines may be considerable. Any scale devised is apt to have great accuracy in the low number range, which is relatively little used, and very little accuracy in the more frequently occurring higher values.

The method which has just been discussed is illustrated by the "straight line diagram" (Leith and Mead, 1915), which has enjoyed wide usage for many years. Its disadvantages somewhat outweigh its advantages. The scale used is a hybrid. The right hand portion (50% to infinity follows the equation $x = m(1 - 100/p)$ where x is the distance, to an arithmetic scale, measured to right and left from a fixed point to points labelled with values of p; p is the percentage relation of any constituent in the unaltered rock to its value in the altered rock, and m is any convenient modulus (Dr. C. V. Theis; oral communication). Thus the 100% point corresponds to $x = 0$. In this part of the diagram equal percentage gains and losses of the constituents plot at equal distances on either side of the fixed point. Considerable importance has been claimed for this feature. However, it is doubtful whether the knowledge that one constituent has suffered a percentage gain equal to the percentage loss of some other, at a given stage of weathering, measurably assists in understanding the processes or trends involved. In fact, the device seems to be a sort of descriptive cul de sac, since, like the graphs of Group I, it omits from consideration the relative amounts or

combining proportions of the constituents. Moreover, the left hand portion of the scale cannot be made to follow the interpretative rule outlined, but is arithmetic, with percentage values of p (as above) so chosen that each 10% interval from zero to 50 has the same length as the 50%–60% interval of the right hand part of the scale. The complication thus introduced, coupled with the loss of two of the advantages listed to this type of graph, makes the retention of the straight-line diagram seem ill-advised. One is reminded of Holmes' remarks on the disuse of Brögger diagrams for igneous rock compositions.

III

The method of gaging progressive changes by comparing the proportions, in altered and unaltered material, of a limited number of groups of substances taken as diagnostic of that progress, has much to recommend it. It has been widely used in comparing and classifying the analyses of igneous and metamorphic rocks, but has not found much favor among students of weathering. It involves several steps in the computations. However, the results graph easily and their significance is readily grasped. The relative proportions of the constituent groups in the individual samples are not lost to view, nor are any assumptions made as to constancy of any of those substances during alteration. Inevitably, any grouping of the components does involve an assumption that those so merged have a similar chemical behavior during weathering. Only two or at most three groups may be utilized conveniently, corresponding to the use of cartesian or triangular plots. Four variables are handled by hard-rock petrographers, who use a tetrahedral figure, and reproduce cuts through it, taken according to some convenient pattern. Similarly, triangular right prisms are sometimes used by the physical-chemist for phase diagrams. However, such systems are cumbersome and it is doubtful whether the accurate analytic data on weathering, as yet available, warrant the use of so detailed and complicated a method.

The process of preparing data in the way now being discussed, involves first recasting the analyses into the form of molecular-ratios.[1] The groups of substances to be taken as representative (in their behavior) of the progress of weathering, are then individually totalled, and these two or three totals refigured to a sum of 100, or 30 or 90 as desired. The resulting figures, which represent the total mol-percentages of the diagnostic groups of substances, are then plotted. If only two groups are taken, a linear scale may be used to show the position of the sample. If three groups are taken, the triangular form of graph, in which each corner represents 100% of one of the three groups, is available (fig. 5). The distance and direction from the plotted point, representing the unaltered rock analysis to that representing the weathered rock, indicate the amount and direction of change. Many analyses can be plotted and numbered on a single graph without confusion. Finally, trends are evident from the relation of the points representing altered-rock analyses to those representing pure sesquioxide-hydrates and clay minerals, which may be taken as possible end points. Since the proportions are figured on a molecular-ratio base, the stoichiometric proportions of these two substances plot very simply. For any point which falls along the R_2O_3–SiO_2 base line (fig. 5), the relative quantity of uncombined R_2O_3 is determined if the type of clay mineral, whose formation is favored by conditions, is known and if there is no free silica.

Decision, as to the use of combined or total silica in group comparisons, must depend upon the data available and on the abundance of primary free silica. Where quartz is relatively scarce in the parent rock, and where secondary silica is known to occur, as in a case of humid-tropical weathering described by Harri-

[1] All FeO is ordinarily recast as Fe_2O_3 and included with the latter.

son and used in figure 5, the relative mobility of SiO_2 would be masked by neglecting its uncombined quantities. Where primary and secondary free SiO_2 are not distinguished, there is no choice but to use total quantities. However, the use of molecular and group ratios is unwarranted in studying the alteration of quartzitic rocks unless the data make it possible to distinguish quantitatively between free and combined silica. Otherwise the stoichiometric proportions are masked by such a nonreactive substance as the former.

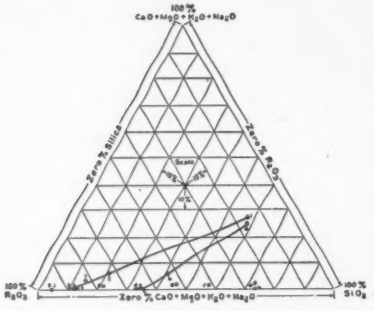

FIG. 5.—Triangular mol-percentage diagram. Progressive alteration of a dolerite under humid-tropical weathering, according to Harrison's data. Base is combined silica for numbered points, total silica for lettered points. 1 and a correspond to fresh rock.

Every system has its weaknesses and the method of comparing analyses now being discussed is no exception. Its usefulness is based upon the possibility of finding two or three substances or groups of substances whose proportional variations truly represent the total progress of rock weathering.

Polynov (1937), following unwittingly in the footsteps of Smyth (1913), believed that he had established the general validity of three groups: (1) alkalis, alkaline-earths and magnesia; (2) silica; and (3) sesquioxides. He based his classification of weathering on them (plus the SO_4–Cl group, which does not concern us here). The possible weakness of his position has been discussed at some length elsewhere. It appears at least probable that no two or three groups of substances have world-wide applicability as indices of the weathering process. Both climatic differences and composition variations of the parent-rock may enter as disturbing factors. Probably, for crystalline rocks under humid climates, the groups quoted are adequate; under other conditions they quite probably are not. However, with sufficient data it is possible that one could pick three representative groups of substances for any given climate and rock type.

The weathering of sedimentary and igneous rocks must differ, both because of unlike proportions of their constituent elements, and, because of the different stabilities of the compounds in which they are united. Some attempts to bring out such variation have been based on adaptations of the triangular diagrams, used by hard-rock petrographers, to weathering studies. The bulk-compositions of the sediments and the igneous rocks are well differentiated by such schemes as Becker's S-U-L and Osann's Al-C-Alk diagrams and the latter has found use in reports of weathering.

In Becker's S-U-L diagram, the apices of the triangle are SiO_2 (Al + Fe + Mg) and (Ca + Na + K). The relative mobilities of the individual substances actually relate magnesia to the third rather than the second group in all cases which have been tested, and since it is by no means an unimportant component, the misgrouping (from the standpoint of weathering) which this involves, rules out this particular scheme.

Osann's Al-C-Alk diagram plots alumina, (CaO + BaO) and the alkalis as the three corners of the triangle. Thus it omits from consideration such important constituents as iron, magnesia and silica. It is interesting as an example of conservatism, that one recent author, after showing conclusively that baria is associated with potassia rather than with lime, both in igneous rocks and in their

weathering, uses this scheme of Osann's which separates them. Actually, of course this difficulty is relatively unimportant since baria is always a minor constituent. The omission of iron and silica, however, makes it impossible to show the character of the end products being approached during weathering, thus the scheme is incapable of indicating weathering directions or potentials.

A more successful method, used by several investigators, consists of a triangular graph on which are plotted the proportions of silica, alumina and combined water. Goldich (1938) follows Edwards (1914) in using combined rather than total silica, a necessity in dealing with quartzose parent materials. The use of weight-percentages rather than mol-percentages, by Mead and by Goldich, and of alumina, instead of R_2O_3, somewhat limit the usefulness of the resulting graph, since neither stoichiometric proportions nor the details of lateritic weathering are comprehended. With the modifications suggested, this method affords a rapid and fairly sensitive approach. It is based on so few variables as to somewhat obscure the directions and potentials of weathering. Thus, among possible parent-rocks, some of the alkali syenites and the diorites and gabbros, plot at almost the same point, although it is improbable that their weathering potentials are so closely related. Similarly, analyses of some magnesian limestones and some black shales, when viewed in this perspective, appear identical.

HYDRATION AND ENERGY-CONTENT

It appears that a simple application of the Smyth-Polynov groups to triangular representation would suffice to bring out whatever the data hold of importance in connection with weathering. However, when a representative shale is plotted in this way it falls well within the field occupied by the common igneous rocks. Since, as is evident, the two do not behave identically in weathering, there must remain unutilized differences between the two types of rock which are significant to their alteration. Three possibilities suggest themselves: (1) the state of aggregation; (2) slight shifts in the concentrations of CaO and Na_2O as contrasted with the sum of MgO and K_2O; (3) the energy-content. Of these the first is a different sort of function than the chemical composition to which both the initial grouping of the constituents noted above and the second and third of the listed differences relate. It could not be shown with consistence on the same plot. The second difference, unfortunately, is not systematic. Different rocks or climates appear to influence both the groupings and the order of abundance of the four constituents named. The matter of energy-content differences between igneous and sedimentary rocks, however, is both characteristic and consistent. While its exact evaluation would be impossible or very tedious in most cases, it seems probable that it is correctly indexed by the degree of hydration, that is, by the H_2O (above 112°) reported in the analyses.

The residual end-products of weathering are chiefly alumino-silicates and sesquioxides. If the correction for energy-content differences suggested above is weighted sufficiently to be effective, and at the same time is not to interfere with the silica-sesquioxide ratio from which the trend of the alteration is to be read, two things follow. First, the correction must be applied to the (CaNaMgK) group, and second, as empirically determined, it involves negative values.

REPRESENTATION OF WEATHERING POTENTIALS AND DIRECTIONS

A scheme which embraces a number of desirable features suggested by the foregoing discussions is presented in figure 6. The upper part of the diagram resembles Becker's S-U-L diagram for igneous rocks, except that MgO is grouped with CaO, Na_2O, K_2O, instead of with R_2O_3. For convenience, the data are plotted on cartesian instead of triangular coordinates, with the abscissa in terms of the

ratios of silica to silica plus sesquioxides. This retains the advantage of showing stoichiometric proportions among the constituents of the end-products approached and at the same time avoids the inconvenience of the infinity term. The lower half of the diagram resembles the silica-alumina-combined water triangle of previous workers, except that molecular ratios are used and that R_2O_3 takes the place of alumina. The water of hydration is here used as an index of the energy-content of the material. It increases as the (CaO, Na_2O, MgO, K_2O) sum diminishes, and its mol-percentage is therefore applied subtractively to that sum. As a result, the points representing the composition of many weathered products fall below the zero line, which comes to have only a relative significance. Vertical distances, then, indicate what may well be termed 'weathering potentials' of materials. The word 'indicate' is here used advisedly, since it seems probable that the true weathering potential may be a negative exponential function of the partial composition, not an arithmetic one such as is shown by the equal-interval scale of the graph. However, data are as yet insufficient to warrant the complication of scale thus suggested. Horizontal distances between successively plotted points express the 'weathering directions' in the sense that they may be used to suggest the end product approached.

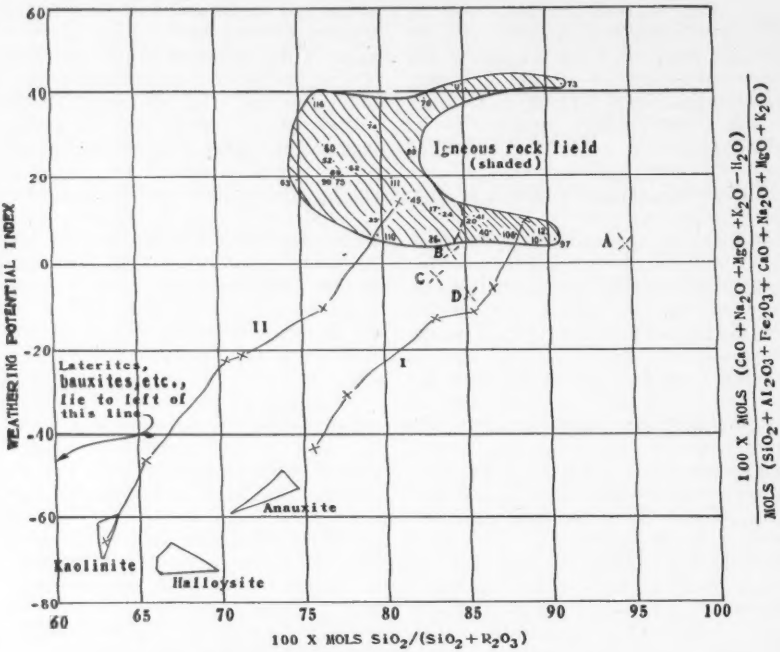

FIG. 6.—Weathering directions and potentials.

To what extent the weathering-potential indices of silicate and of carbonate rocks, as afforded by this scheme, are directly comparable is unsure. Possibly they could be made more nearly so by using a

corrective factor of $(+CO_2 - H_2O)$ in the computations instead of $(-H_2O)$ as is here done. On the other hand, it will be noted, that indices exceeding +42 correspond in general to rocks so high in CaO and MgO as almost to insure a high carbonate content, concentrations of rare hydrates and of evaporites being excepted. The ease of solution-weathering of such rocks, relative to silicates, is therefore at least qualitatively indexed.

Some shale and sandstone analyses will be found to plot within the igneous-rock field shown in figure 6.[2] This may result either from an unusually high content of feldspars, etc., or from calcareous matter. Most of the finer clastic sediments, however, plot outside of and below the igneous-rock field in positions directly indicative of their weathering potentials and tendencies. The single important qualification to this statement applies to all graphic chemical representations; viz., the modifying effects of textural differences on weathering are not taken into account.

In the use of the device just described, one very considerable difficulty is encountered for which there seems no ready solution. Most rock analyses fail to show the quantity of quartz, opal, etc., included with the total silica. The general position of several kinds of rock materials as drawn on figure 6 are all based on total silica. Yet, as has been shown on a previous page, the direction of weathering is obscured by such a procedure if the per cent of quartz is appreciable. If the common igneous rock analyses be recomputed on the basis of combined quartz, the lower arm of the igneous rock field is retracted approximately as indicated by the shading, the remainder of the field being essentially unchanged. Further, if only combined silica be used, the plotted positions of calcareous sandstones and shales move sharply upward and to the left.[3] It appears, therefore, that the fields shown can be used only in a general sense, and in actual studies are of diminished value for quartzose rocks.

An example is given by the two broken lines in the central part of figure 6. The one to the right (I) represents successive compositions in the weathering of granite-gneiss reported by Goldich, figured on a total-silica basis. It appears that an anauxitic end-product is being approached. The same set of data, when computed on a basis of combined silica, gives the line shown next to the left (II) which correctly finds its lower termination within the field of kaolinite as plotted from Ross and Kerr's analyses.

SUMMARY

Weathering graphs may be classified in three main groups. Those of the first group depend on comparisons of the ratios of percentage change of the several constituents and the ratio of change in per cent of some constituent assumed to remain constant in actual amount during alteration. Since the assumption is probably never completely justified, such graphs can have only qualitative value. However, in many cases this is sufficient and the graphs are readily prepared and thoroughly intelligible. Of necessity, they lose sight of stoichiometric proportions so that the end products being approached are not evident.

The second main group includes variation, rectilinear and straight-line diagrams, and depends on comparison of the quantities or proportions of the individual components in the fresh and altered rocks. Variation diagrams require that some important constituent should vary

[2] The numbers on the diagram correspond to tabulated analyses in R. A. Daly's, Igneous rocks and their origin, Table II. McGraw-Hill, 1914. U is an uncompahgrite given by Larsen, E. S.: U. S. Geol. Surv. Prof. Paper 197, p. 36.

[3] The upper-case letters in figure 6 have the following significances:

A. composite analysis of 253 sandstones, by H. N. Stokes; cited by Clarke, F. W., U. S. Geol. Surv. Prof. Paper 770. p. 547, 1924.
B. composite analysis of 27 Mesozoic and Cenozoic shales by H. N. Stokes, idem, p. 552.
C. composite analysis of 51 Paleozoic shales by H. N. Stokes; loc. cit.
D. average of 7 bentonite samples, H. S. Spence, Bentonite, p. 14, Canada Dept. Mines, Mines Branch, 1924.

progressively throughout the series of samples (analyses) in sympathy with the removal of all the others. They may be drawn so as to bring out molecular proportions, and are simple to construct as well as very easy to read. In cases in which no accurate determination of the spatial relations between successive samples can be secured in the field, variation diagrams permit a rational graphic organization of the data in sequence form. They involve no unjustified assumptions. The advantages of the variation diagram are shared by rectilinear graphs which have the additional strength of being suitable for use with very incomplete sets of data. On the other hand, their many correlating sets of lines may render them somewhat confusing. For reasons detailed on page 62, the continued use of the straight-line diagram of Leith and Mead and others seems ill-advised.

In the third group, one compares combinations of constituents instead of individual oxides. Thus general relationships and weathering potentials are more clearly exhibited. The details of changing proportions between the constituents are correspondingly sacrificed. No unwarranted assumptions are necessarily involved. Since ordinarily, molecular ratios instead of weight-percentages will be used to show the combining proportions, the calculations are somewhat tedious. However, the graphs are readily intelligible.

The desirability of using molecular ratios and mol-percentages, rather than weight-percentages, wherever feasible, is evident from the discussion. Similarly, weathering studies should ideally comprise a number of analyses of samples at consecutive stages in the process as in the report of Goldich previously cited. His study is also exemplary in making it possible to differentiate quartz and combined silica, a necessity if the directions of weathering are to be established.

Clarke (1924) comments on the fact that different weathering studies cannot be compared, since the influences of climate, rock chemistry, exposure and drainage, and textural character are not evaluated. If this barrier is to be overcome, future studies must be more explicit along the lines indicated. It is unfortunate that most of the few reasonably thorough descriptions now available concern ancient examples of alteration, for which the climate, drainage, etc., can only be estimated. Soil studies too often stop at the top of the C-horizon, but Jenny's evaluation of the factors involved is an important move in the right direction.

Finally, it may be emphasized that graphic representation of weathering studies should follow schemes designed for the purpose and not be slavishly patterned on devices intended for quite different uses. It is hoped that the scheme of figure 6 may be found helpful, and that it may be improved and corrected by others.

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JOURNAL OF SEDIMENTARY PETROLOGY, VOL. 13, NO. 2, PP. 69–78,
FIGS. 1–7, TABLES 1–5, AUGUST, 1943

SHAPE AND ROUNDNESS OF LAKE ERIE BEACH SANDS

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ABSTRACT

Seven beach sand samples were collected at mile intervals along Cedar Point spit on the south side of Lake Erie. Shape and roundness analyses were made on the light, carbonate-free fraction of the six size grades common to all samples. Sphericity declined slightly and roundness considerably in the direction of sand shift. The feldspar content, about 25 per cent, was unchanged.

Data obtained in this study and the published field and laboratory work on other sands, shows that simple abrasion cannot account for the observed trends. Water currents, sorting the sands of the beach in the down-current direction, carry the less spherical grains further than the more spherical, other things being equal, and since roundness was found to be closely correlated with sphericity, concomitant roundness decline takes place. The correlation of roundness and sphericity is the result of abrasion in earlier cycles of sedimentation.

INTRODUCTION

The manner and conditions under which sand grains become rounded have long engaged the attention of geologists. Many opinions but few facts have been contributed by earlier workers. Most noted exception is the excellent study of Russell and Taylor on the shape and roundness of river sand published in 1937. This work, based on quantitative laboratory study of a series of samples collected from the Mississippi River, between Cairo, Illinois, and the Gulf of Mexico, showed that roundness (and sphericity) declined as the sand was shifted about 1100 miles seaward. This unexpected observation was explained as the result of fracturing and splitting of the grains during transit. Russell and Taylor concluded, therefore, that if the Mississippi is typical, that rivers do not customarily round sand and that the place of sand rounding had to be sought elsewhere.[1] Russell (1939) later said that the most favorable sites for the rounding of sand grains appear to be areas of sand concentration. These are the dunes and sand beaches.

It seemed, therefore, that beaches should be studied to ascertain the manner and rate of sand rounding. To this end the authors examined a series of samples collected from the lakeward side of Cedar Point, a prominent spit formed across Sandusky Bay on the south side of Lake Erie. The grain size and mineral composition of these samples were described in some measure at an earlier date (Pettijohn and Ridge, 1932 and 1933).

The samples were collected by Charlotte Webster Barnes in 1931. The laboratory analyses were largely performed by the junior author.

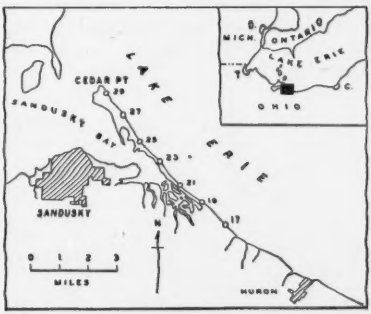

FIG. 1.—Collection localities, Cedar Point, Ohio.

[1] Krynine has taken exception to Russell's conclusion and states—without evidence—that he has observed sand rounding in some New England streams (Krynine, 1940).

FIELD RELATIONS

Cedar Point is a sandy spit, about seven miles in length, attached at its easterly end to the mainland, built across Sandusky Bay by littoral currents which move from east to west. The currents, therefore, move against the prevailing winds of the region. This anomaly has been observed by others, notably Johnson (1919), and is accounted for by the difference in fetch and hence effectiveness of waves generated by westerly and easterly winds. The westerlies have but short fetch owing to the island archipelago which lies athwart the lake a few miles west of Sandusky Bay. A few northeasterly gales from the long island-free sweep eastward will move more sand westward than many a westerly breeze can shift back again.

The beach materials are derived from (1) the sediments of glacial lakes Warren, Whittlesey and Maumee; (2) the glacial till; (3) the black Huron shale which forms the local bed rock; and (4) subaqueous erosion of whatever material lies beneath the surface of the lake and is still within reach of effective wave action. Wave erosion of the mainland provides most of the material. Material of immediate or ultimate glacial derivation dominates.

Beach samples were taken, a half mile apart, midway between high and low water limits. Every alternate sample from the spit proper was analyzed in the laboratory. Seven samples in all were studied in detail.

LABORATORY ANALYSES

Preliminary treatment

Each sample was properly reduced by a Jones-type sample splitter, acid-treated to remove calcareous matter, dried and run through a nest of sieves. Six size fractions common to all samples—42 fractions in all—were then separated into light and heavy portion with acetylene tetrabromide (S.G. 2.96). The light separates, mainly quartz and feldspar, were further reduced in bulk by a Microsplit and a representative microfraction was mounted in piperine ($n = 1.68$). Each of the 42 slides thus prepared was microprojected.

Sphericity

The sphericity of 50 random grains was determined from the projected grain images by the Riley Method (Riley, 1941). This method involves the measurement of the diameter of the inscribed and circumscribed circles. The sphericity is given as $\sqrt{d_i/d_c}$, where d_i and d_c are the diameters of the inscribed and circumscribed circles, respectively. This value has been shown to correlate well with the laboriously-derived Wadell projection sphericity (table 2). Owing to the inability of this or any other projection method to distinguish a disk from a sphere, the sphericity values obtained were in some degree misleading. Hence a microfraction of three size classes of three samples was taken and placed as a dry mount under the microscope. The loose grains tend to rest with the *a* and *b* di-

TABLE 1. *Size and sorting.*

Sample Number	Geometric mean size mm.	Phi mean	Phi standard deviation
17	.38	1.37	.534
19	.39	1.35	.497
21	.26	1.97	.641
23	.24	2.04	.520
25	.21	2.24	.496
27	.18	2.51	.541
29	.17	2.60	.579

ameters parallel to the plane of the slide. c tends to be normal to the same surface ($a > b > c$). a, b, and c were determined on 25 grains in each of the nine fractions by means of micrometer ocular and micrometer focusing screw. The b/a and c/b ratios were computed and plotted on a Zingg chart on which the curves representing Wadell sphericity values had been drawn. Such a plot for each separate made it possible to determine graphically the sphericity of each grain and to group the values into appropriate classes and thus compute the mean sphericity and standard deviation (table 3). This method has been shown to give sphericity values which agree very closely with values obtained from the volume methods of Wadell designed for pebbles (Krumbein, 1941a) and it is believed to yield reliable figures, therefore, for sand grains.

TABLE 2. *Sphericity values determined by the Riley method.*

Size Grade mm.	17	19	21	23	25	27	29	Arithmetic mean
.701–.495	.87	.82	.84	.83	.80	.82	.84	.830
.351–.246	.81	.80	.79	.83	.77	.80	.80	.800
.175–.124	.77	.77	.76	.81	.75	.77	.79	.774
Arithmetic mean	.81	.79	.79	.82	.77	.79	.81	

Number of grains measured in each separate—50

TABLE 3. *Intercept sphericities.*

Sample Number	Size Grade mm.	Arithmetic mean	Standard deviation
17	.351–.246	.760	.0145
23	.351–.246	.744	.0106
29	.351–.246	.730	.0140

Number of grains measured in each sample—25

Roundness

The roundness of each of the six size fractions of the seven samples was determined by a visual method. The 42 mounted separates were projected and 50 grains, randomly chosen, and compared with a standard chart on which ten roundness classes were represented (see Krumbein 1941a). The roundness of each grain was estimated and the average roundness of each separate computed. (table 4). This very rapid method has been shown to give excellent results for pebbles and is in principal similar to that used by Russell and Taylor and found by them to yield reproducable results (Russell and Taylor, p. 244). The roundness values correlate closely with those achieved by the more rigorous methods detailed by Wadell.

Feldspar content

Studies of roundness and sphericity should be limited to one mineral. The light separates from the acidized beach sand contain, however, not only quartz but an appreciable quantity of feldspar. Hence to know what influence, if any, the feldspar might have on the results, the feldspar content had to be determined. Ready identification of acid feldspar in a quartz-feldspar mixture is best

TABLE 4. *Roundness values determined by the visual-comparison method.*

Size Grade mm.	17	19	21	23	25	27	29	Arithmetic mean
.701–.495	.440	.434	.431	.400	.410	.430	.380	.418
.495–.351	.400	.380	.400	.360	.420	.410	.351	.388
.351–.246	.400	.375	.360	.360	.350	.340	.334	.360
.246–.175	.320	.333	.355	.350	.300	.328	.280	.324
.175–.124	.330	.326	.306	.341	.270	.266	.320	.308
.124–.088	.270	.290	.290	.321	.293	.260	.310	.290
Arithmetic mean	.360	.356	.357	.355	.340	.338	.329	

Number of grains used in each separate—50

achieved by the method of selective staining outlined by Russell (1935). The feldspar content of three size fractions of the seven investigated samples was determinded. The results are given in table 5.

While the study is primarily concerned with the changes in shape and roundness of the sand as it is shifted along the beach,

TABLE 5. *Per cent of feldspar.*

Size Grade mm.	Sample Numbers							Arithmetic mean
	17	19	21	23	25	27	29	
.701–.495	21	25	31	32	29	27	36	29
.351–.246	31	24	22	21	24	23	23	24
.175–.124	20	21	20	18	25	18	27	21
Arithmetic mean	24	23	24	24	26	22	28	25

ANALYTICAL RESULTS

Size

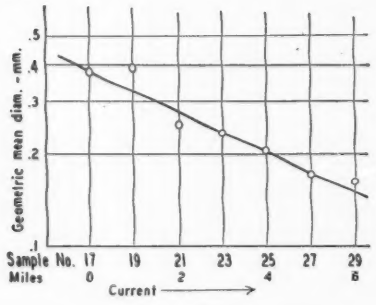

FIG. 2.—Relation of geometric mean diameter of sand sample to position on beach.

it is not possible to discuss these properties without considering the grain size. Since the size changes have been reported on elsewhere, table 1 and figure 2 will suffice to summarize this earlier work. The mean size of the sand along the spit decreases markedly. As noted in the figure this decrease follows a negative exponential law. The rate of decrease is expressed by an equation of the type $y = mb^{-ax}$. From the graph the coefficients may be determined and the equation written $y = y_0e^{-ax}$ or $y = .38e^{-.157x}$.

Sphericity

The sphericity values obtained by measurements on the grain projection show no clear trend with distance of transport. The values fluctuate within a very small range (table 2). What is evi-

dent, however, by inspection of the table, is the relation between sphericity and size. The average of the coarser fraction (.701–.495 mm.) is .830 while that of the finer fraction (.175–.125 mm.) is .774, a difference of about six per cent. In every sample the larger size was found to be the most spherical. This is in accord with the experiments of Thiel (1940) in which crushed quartz was abraded in a revolving drum for 100 days (about 8000 miles of travel) at the end of which time the coarser grains (2–1 mm.) had a sphericity of .79 and the smaller size (1–.5 mm.) had a sphericity of .71. The initial sphericities of the two sizes of crushed quartz were .72 and .70 respectively. Similar results were obtained with other minerals including microcline. Russell and Taylor (1937, p. 250) also discovered a definite relation between size and sphericity of sand grains. The 35 mesh fraction (average of 3 samples) had a sphericity of .84; the sand retained on the 150 mesh had a sphericity of .79. These values approximate those of the Cedar Point samples for the comparable sieve fractions.

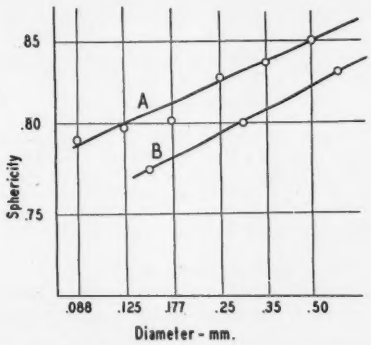

FIG. 3.—Relation of log arithmetic mean sphericity and log geometric mean diameter of size grades investigated. A, arithmetic mean of three samples Mississippi River sand (Russell and Taylor); B, arithmetic mean of seven beach samples (Pettijohn and Lundahl).

Data are not adequate to determine certainly the nature of the function represented in table 3, nor can the function be definitely ascertained unless the sphericity values are those computed from diameter intercepts instead of projected images.

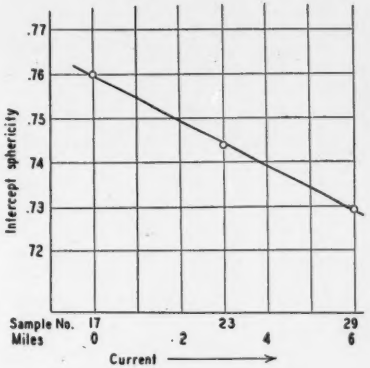

FIG. 4.—Relation of arithmetic mean sphericity of .35–.25 mm. size grade and position on beach.

The sphericity of the grains in the same size class (.35–.25 mm.) of the three samples based on diameter intercepts (*a*, *b*, and *c*) does show a small though unequivocal decline in the direction of sand movement (table 3 and fig. 4). The decline amounts to four per cent in seven miles.

Roundness

The relationship between roundness and distance of travel is much clearer. All size classes show a definite, though fluctuating, decrease in average roundness with distance of travel with the possible exception of the finest grade (table 4). The unweighted mean of all grades shows an almost unvarying decline (table 4 and fig. 5). The decrease is .360 to .329 or a decline of a little more than eight per cent in seven miles. The .35–.25 mm. class, for which intercept sphericity values were obtained, declined 17.5 per cent. Russell and Taylor report a roundness decrease (Wadell method) of .239 to

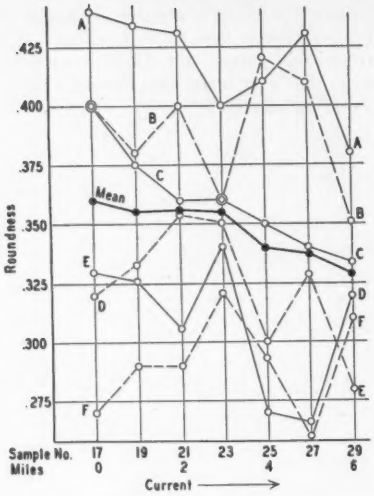

FIG. 5.—Relation of arithmetic mean roundness of each size grade and position and unweighted arithmetic mean roundness of whole sample and position on beach. A, .70–.50 mm. class; B, .50–.35 mm. class; C, .35–.25 mm. class; D, .25–.177 mm. class; E, .177–.125 mm. class; F, .125–.088 mm. class.

.179 or 23.5 per cent in nearly 1100 miles of travel. The data for the Mississippi and the Lake Erie beach are not wholly comparable since the mean grain size of the samples are unlike.

A well-defined relationship exists between size and roundness. The larger sizes are much better rounded than the smaller grades (table 4). The functional relation between them can readily be established by plotting log size against log roundness (fig. 6). The data plot as a straight line which means that the relation is mathematically of the type $y = mx^n$. From the plot the coefficient and the value of the exponent can be determined so that the expression may be given as $y = .46x^{.21}$. A similar relationship between roundness and size was noted by Russell and Taylor in the Mississippi River sand (1937, p. 250) and by Wadell in the St. Peter sand (Wadell, 1935, p. 277) and by others.

Since roundness and sphericity are both functions of grain size it follows that they must be functions of each

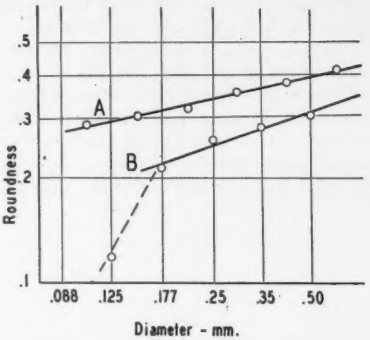

FIG. 6.—Relation between log arithmetic mean roundness and log geometric mean diameter of each size class. A, average of seven samples Lake Erie beach sand (Pettijohn and Lundahl); B, average of three samples, Mississippi River sand (Russell and Taylor).

other. Figure 7 shows the relations observed. Curve *B* shows the average Riley sphericity number plotted against the

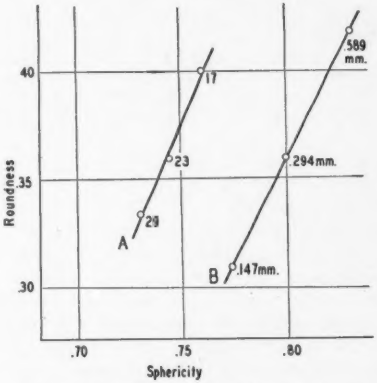

FIG. 7.—Relation of sphericity and roundness. A, intercept sphericity values for .35–.25 mm. size class; B, arithmetic means of projection sphericity values for the size classes shown from seven samples.

average roundness for three grade classes of all samples. Curve *A* shows the Zingg-

Krumbein sphericity values of the .351–.246 mm. grade in the three samples plotted against the roundness values of the same. The relations are essentially the same in both curves. Curve *B* is displaced to the right from *A* since, as earlier noted by Wadell (1935, p. 265) projection sphericities err in being too high compared to sphericities determined by volume or intercept measurements.

Russell and Taylor noted a similar correlation in the Mississippi River sands and a like relationship is apparent in data published by Wadell (1935, p. 276). As noted by Russell and Taylor (p. 348) a small change in sphericity is associated with a relatively greater change in roundness. The relation is apparently linear. In curve *B* a sphericity increase of 7.9 per cent carries with it a 35.8 per cent increase in roundness. In curve *A* the values are 4.1 per cent and 21.2 per cent respectively.

Feldspar content

The feldspar content of the acidized light fraction averages 24.5 per cent. This is but very slightly higher than most sands of glacial derivation. Twenty-two Illinois river sands, for example (Willman, 1942) average 21 per cent; the Mississippi River sands of Russell and Taylor averaged about 20 to 25 per cent (1937, p. 252). The seven Lake Erie samples ranged from 22 to 28 per cent. No trend in direction of shore drift is apparent (table 5). This stands in contrast to a slight decline observed by Russell and Taylor in the coarser fractions of the Mississippi River sand.

As can be seen in the table, the coarser fraction has more feldspar (29 per cent) than the finest fraction analyzed (21 per cent). This is just the opposite of the findings of Martens (1931, p. 531) for Florida beach sand. Russell and Taylor (p. 254) found a correlation between roundness and the feldspar content. High quartz (and low feldspar) was correlated with lower roundness. No correlation was observed in the Lake Erie beach materials. Apparently quartz and feldspar are near enough alike mechanically so that the very considerable feldspar content can be overlooked in interpreting the observed trends in sphericity and roundness in direction of sand movement.

GEOLOGICAL SIGNIFICANCE

Russell and Taylor's Mississippi River study—foreshadowed in some degree by earlier work on beach sands by McCarthy (1933)—presents a dilemma. On the one hand, we have experimental work by Thiel, in which sand grains were progressively rounded and made more spherical by abrasion in a revolving drum, and on the other, the field and laboratory studies by Russell and Taylor (and McCarthy), in which sand grains during transit are apparently made less spherical and less rounded. As noted, Russell concluded that large rivers do not habitually round sand and that places of sand accumulation, notably beaches, were the places where sands were rounded. This contention is apparently contradicted by the study of the sands of Cedar Point in Lake Erie. The logical deduction, therefore, is that the sand grains are round when created and all sedimentary processes tend to make them angular.

This *reductio ad absurdum* can be resolved only if the two processes operating on particles in transit in fluids be fully understood and kept in mind. These are the abrasive processes, tending toward size reduction, and the selective processes which sort and classify on the basis of size, shape and specific gravity. The first alone is operative in the abrasion mill experiments. Both operate in nature though one may dominate and mask the effects of the other. The observed effects of one have often been erroneously attributed to the other.

A sand grain apparently gets smaller, more spherical and better rounded as a result of abrasion. Exceptionally—when coarse material is abundant—the grains tend to split and fracture and are converted to silt and mud (Marshall, 1927).

On the other hand abrasive action in the absence of coarse materials is exceedingly slow as shown by every experimenter. Anderson's (1926) work on the rate of wear of sand grains is amply substantiated by Thiel's (1940) data. Thiel's mill revolved 100 days—about 8000 miles—yet the quartz grains were but very little rounded. The various properties—size, sphericity, and roundness—are not equally affected by the abrasive process. As shown by Krumbein (1941b) for gravels, rounding proceeds more rapidly than shape modification which in turn is more rapid than size reduction. For limestone pebbles the ratio of rounding to shape change was 19.5 to 1 while that of shape change to size was 2.5 to 1. Ingerson and Ramisch (1942) showed that the shape of the quartz grains of the St. Peter sandstone was an inherited characteristic, i.e., inherited in the main from the ultimate source—namely a granitic igneous rock. If this be true of a sediment such as the St. Peter sandstone composed of many times reworked grains, it can be safely said that one cycle of sedimentation makes no appreciable modification of the size and shape of the grains and very little change in roundness. It seems highly improbable, therefore, that the marked size reduction[2] observed on the Cedar Point spit could be due to abrasion and in the absence of coarse material to breakage or fracture.

Selective transport, therefore, must explain the observed size, shape and roundness trends. Size, shape and density are the grain properties governing the sorting process. The Cedar Point data, together with the observations of MacCarthy and Russell and Taylor, support the theses that (1) the large grains tend to outrun the small in the downcurrent direction; (2) the less spherical tend to outrun the more spherical; and (3) minerals of lower density tend to outrun minerals of higher density. Suspension transport is implied. Since quartz and feldspar have nearly the same density, only the first two propositions are important in this discussion.[3]

The composition of the beach sand at any point is controlled by the sorting action. Nevertheless the constitutent grains have had an abrasion history. The source materials are diverse and are only in part first cycle. Many well-rounded and highly spherical grains, products of earlier cycles of transport and abrasion, are present. Accordingly the littoral currents have not only a diversity of sizes to work on but also a diversity of shapes and correlated roundness. While sphericity and roundness are geometrically distinct they react in a dynamically similar manner to abrasion so that there is a close correlation between the two. Experimental work shows that a small increase in sphericity is accompanied by a larger increase in roundness. Consequently, if grains are selected on the basis of sphericity and if the grains of lower sphericity outrun those of more spherical shape—other things being equal—then the down-current decline in sphericity—as noted by MacCarthy (1933), Russell and Taylor (1937), and by the present writers—should be accompanied by a correlative decline in roundness.

Russell and Taylor recognized selective sorting as a process capable of producing the observed results but dismissed it in favor of progressive fracturing. They dispose of the selective sorting hypothesis on the grounds that the decrease in roundness was five to ten times greater than the decrease in sphericity and, therefore, the decrease in roundness was the primary effect and the decrease in sphe-

[2] The size decline here observed, .374 to .125 mm. is very large. Reduction of .25 to .125 mm. in diameter involves the wearing off of seven-eights (87 per cent) of the volume of the grain. Present data suggest that size reduction of this amount never takes place. How otherwise would multicycle St. Peter grains retain their original shape?

[3] See discussion of Pettijohn and Ridge (1933) on heavy mineral changes in the downcurrent direction of the Lake Erie spit. See also Smithson (1939) for further exposition of the third thesis.

ricity the result. This argument has little validity in light of recent experimental work just pointed out.

Conclusive evidence for the Mississippi sands, according to Russell and Taylor, is afforded by comparison of the sphericity decline observed in the river sands with that observed in beaches. MacCarthy's data are cited and a sphericity decline of 5.5 per cent in 128 miles of travel down beach is contrasted to 1.9 per cent decline in more than 1050 miles of river travel. The contrast is still more striking if the 4 per cent sphericity decline in seven miles along Cedar Point be considered. Comparison of beach and river travel, or even comparison of two beaches, is likely to be misleading. River travel is unidirectional whereas beach movement is oscillatory. A sand grain may well travel twenty feet back and forth normal to the beach to progress laterally but one foot. Moreover absolute distance is meaningless in a *sorting* phenomenon. A complete range of sizes, shapes, or densities may be perfectly sorted out in few inches in a miner's pan or may be spread over many yards or even miles in nature.

Russell and Taylor's final argument is based on the lesser diminution in sphericity shown by the smaller sizes. Sphericity decline due to sorting requires suspension transport. The small grains, therefore, according to these authors, should exhibit the larger change since they are more readily carried in suspension. The argument is a theoretical one with no experimental data to support it and until the latter be forthcoming, it will have to be taken with reservations. Sorting is such a complex phenomenon that it is doubtful whether we can predict what ought to happen. For some time we shall have to be content with seeing what does take place.

In summary it may be said that simple abrasion alone will not account for the observed properties of the Cedar Point beach sands. The sphericity and roundness trends observed all run counter to experimental abrasion studies on sand.

Appeal to fracture of grains provides only a partial explanation which is, moreover, not wholly satisfactory. It is inadequate partly because coarse materials needed for sand destruction are absent. It is inadequate also because if fracturing be appealed to then there remains no place for rounding of sand grains. It seems highly improbable, furthermore, that the waves of Lake Erie provide such rigor of action required to produce the extraordinary size reduction observed. It is very unlikely that the rigor of the lake beach is higher than that under which such perfecrly rounded sands such as the St. Peter accumulated.

Selective sorting of materials of diverse nature is the only complete and wholly consistent explanation. Multicycle grains of quartz mingled with first cycle glacial quartz provide a range of sizes, shapes and correlative roundings, on which the westward-movement littoral currents operate. The more rapid migration of the less spherical grains coupled with the lagging behind of the more spherical forms of the same size grade is in accord with Wadell's theoretical prediction (1932). Suspension transport is implied. The apparent sphericity decline carries with it a larger concomittant roundness decrease as is to be expected from abrasion experiments. Thus it is possible for each sand grain carried along the spit to become progressively a little more rounded and yet to have the aggregate or sample collected at any one point to have a lesser roundness grade for grade than a similar sample collected nearer the landward end of the structure, i.e., in the "upcurrent" direction.

Extreme caution should be exercised in attributing any change in size, shape or roundness observed in direction of travel, to abrasion and reasoning, based on the assumption that such changes are due to abrasion (see Shulitts, 1941), is definitely suspect.

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JOURNAL OF SEDIMENTARY PETROLOGY, VOL. 13, NO. 2, PP. 79–81,
FIGS. 1–2

A VISUAL METHOD OF ESTIMATING TWO-DIMENSIONAL SPHERICITY

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ABSTRACT

The two-dimensional sphericity of sands and other fine-grained particulate materials may be determined rapidly by visual comparison with a chart (fig. 1). Mean sphericities so obtained are sufficiently accurate for many types of investigations.

As part of an intensive study of the transportation and deposition of heavy minerals in the Middle Rio Grande Valley, N. M., it was necessary to obtain information on the shape (sphericity) of the light and heavy minerals. Time was not available to obtain sufficiently comprehensive data by the tedious methods then in common use. A visual method, based on Wadell (1935) projection measurements of grain shape, was developed and tested. Although discarded in favor of a procedure that gave three-dimensional shape data (Rittenhouse, 1943), visual determinations of grain shape may be used to advantage in several ways, notably, (1) for consolidated sediments or particles having secondary growths; and (2) for correlation or description. Consequently, publication of the chart used for visual comparisons seems desirable. By using this sphericity chart and Krumbein's (1941) roundness chart, rapid determinations of both sphericity and roundness are possible.

In preparing the chart (fig. 1), enlarged camera lucida drawings were made of a large number of sand grains. The Wadell projection sphericity (1935) was computed for each grain from the longest diameter and the projection area as measured by polar planimeter. The sphericity range from .98 to .44 was divided into units of .02 and five grains of varying roundness were selected to represent each unit.

To determine sphericity by visual comparison, loose or permanently mounted grains are magnified by microscope or microprojector to about the size of those in figure 1. The sphericity of each grain is estimated by comparison with the outlines on the chart. Best results are obtained by first selecting sphericities on the chart that are obviously too high and too low and then narrowing this range. By the visual method, sphericities may be determined at the rate of one or two per minute.

Before using the chart for samples of sediments it is suggested that sphericities be estimated for the eighteen grains of figure 2. The Wadell projection sphericities for these grains (from left to right in each row) are as follows: .80, .72, .67, .60, and .62; .70, .85, .68, .85, and .56; .89, .67, .87, .70, and .63; .74, .76, and .74. The mean sphericity of these grains is .725. If necessary the sphericities should be redetermined until mean and individual values approximate the Wadell values.

To compare the results obtained by the visual method with those by the Wadell (1935) and Riley (1941) methods, a series of measurements were made on the eighteen grains of figure 2. Mean sphericities were as follows: Wadell, .725; Riley, .722; visual, .714. For individual grains the maximum deviation of visual sphericities from Wadell values was .07. About two months later mean values of .718,

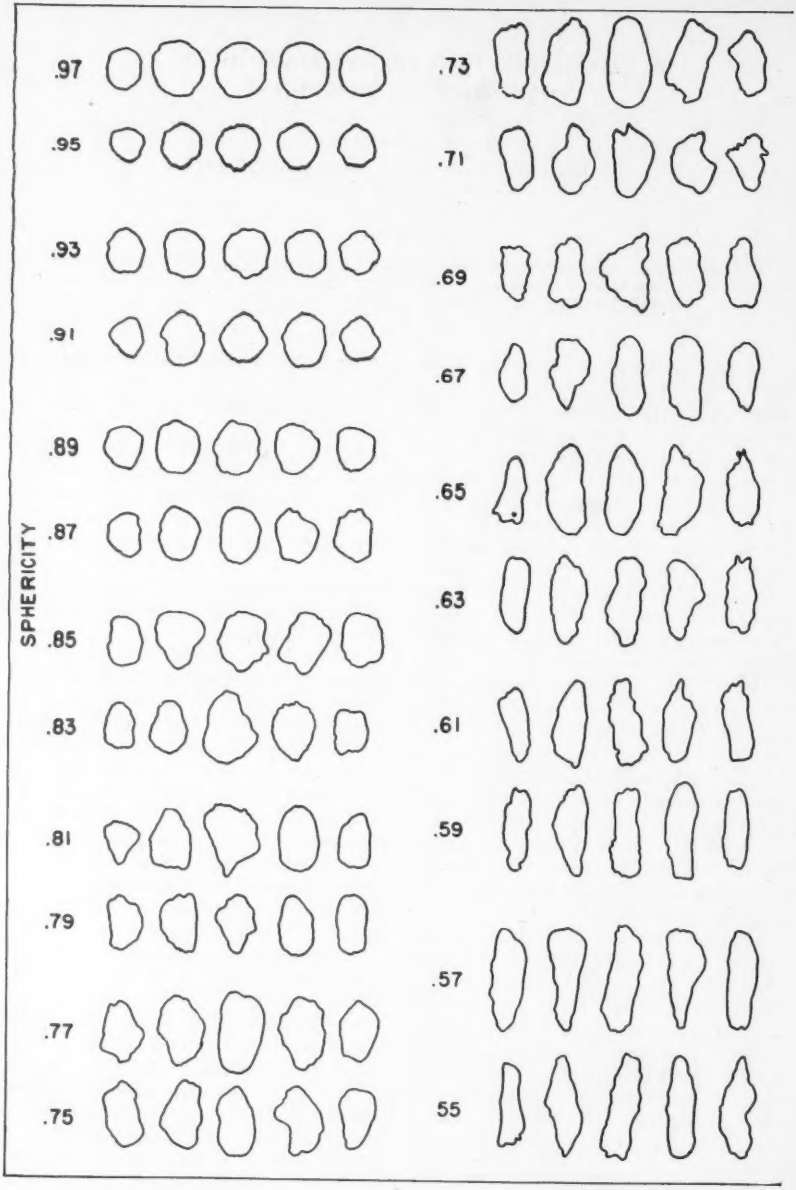
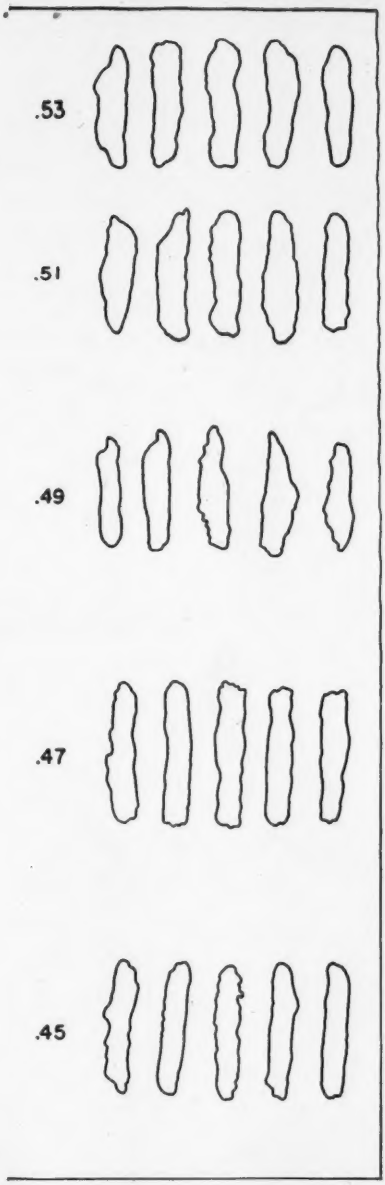


FIG. 1.—Chart for determining visually the projection sphericity of sands and other particulate materials.



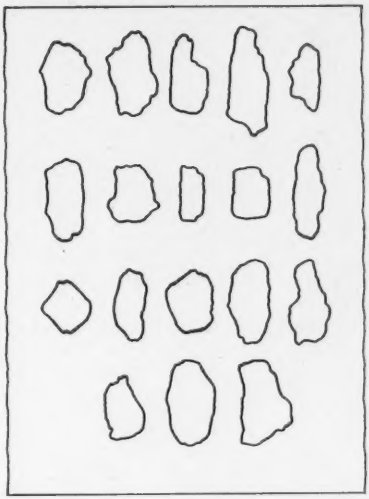


FIG. 2.—Grains of known Wadell projection sphericity (see text).

.714, and .713 were obtained by visual comparisons on the same grains. Fifteen months later remeasurement yielded a visual sphericity value of .703. At the time of this last determination, the chart had not been used for about a year.

Considering the rather large sampling errors to which sphericity studies are subject, it seems probable that visual comparisons will yield data of sufficient accuracy for many investigations. Certainly the rapidity of visual comparison will permit shape studies to be made a part of many investigations in which the time available otherwise would be insufficient.

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